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Micro combined heat and power (MCHP) technologies and applications

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ABSTRACT

Micro-cogeneration, also termed micro combined heat and power (MCHP) or residential cogeneration, is an emerging technology with the potential to provide energy efficiency and environmental benefits by reducing primary energy consumption and associated greenhouse gas emissions. MCHP can help to meet a number of energy and social policy aims. These are the reduction of greenhouse gas emissions from energy supply, increased decentralization of energy supply, improved energy security, possible avoidance of investment in and energy losses from electricity transmission and distribution networks, and potentially reduced energy cost to consumers. Micro-cogeneration systems have the potential to reduce energy demands of the residential sector for space heating, domestic hot water heating, and electricity. The reduced greenhouse gas emissions and reduced reliance upon central electrical generation, transmission, and distribution systems are the possible benefits. Also in the present paper, a comparison has been made between the MCHP technology and the other ones such as prime mover, electrical and thermal power, efficiency and emissions.

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1. Introduction

In some of the countries the CHP (combined heat and power) system has been integrated into power network to generate both electricity and useful heat, and to offer a tremendous increase in revenue to declining fossil fuelled emissions, while saving operational costs for power generation by capturing some or all of the by-product heat [1–3]. In recent years, combined heat and power systems (CHPs) that generates both heat and power with high efficiency have received considerable attention. Small scale CHPs also referred to as domestic (dCHP) or Micro CHPs (MCHPs) have found niche markets in domestic and office application due to the ability to rapidly vary their electrical load to reduce or increase the thermal output [4–6]. Small in terms of power output (usually less than 5 kW_{el}), the portability and simplicity of MCHP allowed them for installation in millions of homes, particularly where there is a huge market for heating fuel. In such applications, the MCHP serves as the central heating unit providing heat and hot water and additionally supplies the electrical power requirements, for domestic appliances [4,7]. Globally, pre-commercial projects have already been initiated for the implementation of MCHP systems on the larger scale. A fuel cell-based CHP (FC-CHP) system converts on-site, the chemical energy in the fuel into electrical power and heat with an overall efficiency of around 80–90% [8,9].

Micro-cogeneration systems have the potential to reduce energy demands of the residential sector for space heating, domestic hot water heating, and electricity. The reduced greenhouse gas emissions and reduced reliance upon central electrical generation, transmission, and distribution systems are the possible benefits [10].

The combined heat and power generation (CHP) or cogeneration has been considered worldwide as the major alternative to traditional systems in terms of significant energy saving and environmental conservation [11]. Some of the researchers argue that heat should always be produced along with the power whenever possible [12]. The most promising target in the application of CHP lies in energy production for buildings, where small-scale and Micro-scale CHP is usually installed [13]. Generally speaking, the concept “small-scale CHP” means combined heat and power generation systems with electrical power less than 100 kW. “Micro-scale CHP” is also often used to denote small-scale CHP systems with an electric capacity smaller than 15 kW_e [14].

The small-scale and Micro-scale CHP systems are particularly suitable for applications in commercial buildings, such as hospitals, schools, industrial premises, office building blocks, and domestic buildings of single or multifamily dwelling houses. These systems can help to meet a number of energy and social policy aims, including the reduction in greenhouse gas emissions, improved energy security, investment saving resulted from the omission of the electricity transmission and distribution network, and the potentially reduced energy cost to consumers [15]. A Micro CHP system is also able to provide a higher degree of reliability since the system can be operated independent of the grid if there is a black out [16]. Currently, Micro-scale CHP systems are undergoing rapid development, and are emerging on the market with promising prospects for the near future [13,15]. UK has been predicted to become one of the three largest markets for Micro CHP installations in Europe [17].

In UK, the Government has committed to reducing national greenhouse gas emissions by 12.5% based on the first Kyoto Protocol commitment period, and has reaffirmed its low-carbon aspirations in the more recent energy white paper which suggests 60% emissions reduction by 2050 [18]. Although the UK aspirations are more aggressive than some others, the low-carbon trend is apparent across Europe and all countries that ratified the Kyoto Protocol. Some of the countries that have not ratified Kyoto (USA and Australia) are pursuing similar goals through technology led strategies. Micro CHP, in the form of Stirling engines (SE), gas engines, and fuel cells can assist in achieving greenhouse gas emission targets [19], with some estimates of reduction between approximately 500 kg and 1000 kg CO_2 emission per year per household in the UK for 1 kW_e units [20]. For Stirling engines and fuel cell MCHP systems in UK single-family houses (SFH), Peacock and Newborough [20,21] predicted 9% and 16% of CO_2 emissions savings compared to condensing boiler and grid electricity, and even greater savings for higher power output systems of high efficiency, with larger portions of generated electricity being exported [22]. A comparative CO_2 savings assessment of fuel cell (FC), Stirling engine (SE) and internal combustion engine (ICE) MCHP and heat pumps for the UK domestic sector was made by Cockroft and Kelly [23,24] (Fig. 1).

As shown in Fig. 1, gas engine has minimum CO_2 saving and solid oxide fuel cell has maximum CO_2 saving. Since the most feasible applications (in terms of both primary energy saving and

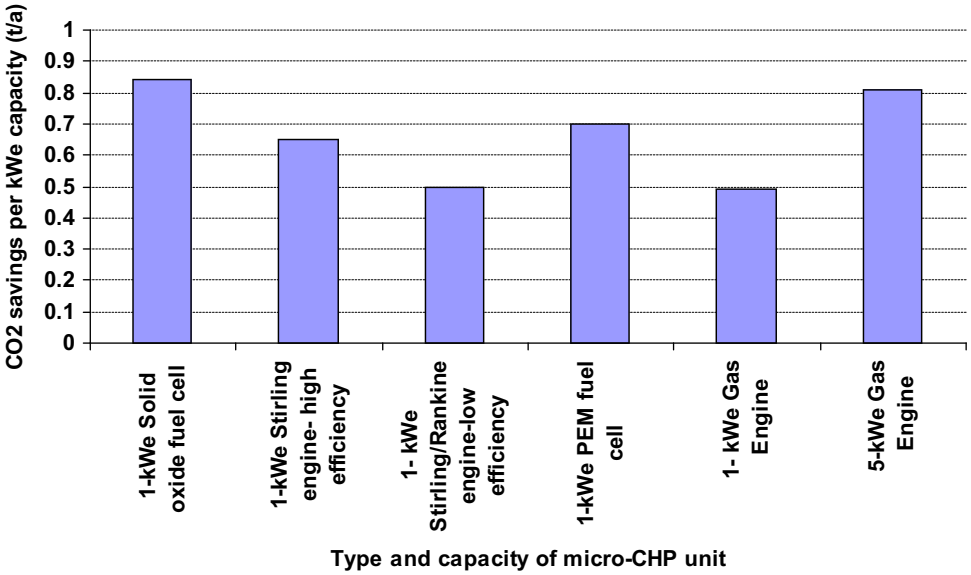


Fig. 1. Annual Micro CHP CO_2 saving compared to grid electricity and boiler alternatives [24].

economic profit) for CHP in the industry scenario have already been exploited, as testified by [25–27] for medium and large users, today the main potential for CHP diffusion seems to be in the residential sector. Until the present, even though (i) the interest in domestic Micro CHP began in the late 1980s, as shown in a pioneering study of the application of small-scale CHP systems to building services [28] and (ii) it was analytically demonstrated that distributed CHP systems increase the site fuel energy consumption [29], by reducing the primary energy consumption, several technical [30–32], environmental [20], economic [33] and legislative [34] problems have curbed the spread of CHP technology in this sector, especially for electric power sizes of a few kW [35]. One of the main difficulties is that the currently available CHP technologies in this range of electric power output, which are basically internal combustion engines, do not have the characteristics of high efficiency, low cost, silent operation, low pollutant emissions and reduced maintenance, to render the CHP a real option as a substitute or as an integration of the traditional household boiler [30]. A simplified layout of the CHP integrated system investigated in this study is presented in Fig. 2. The CHP systems used for the heating of residential buildings are usually interconnected with the energy which can be sent to the users or, when there is surplus production, to the external electric network. On the contrary, when the instantaneous electric demand is higher than the CHP electric power, the external electric network supplies the electric power difference between demand and production. Therefore, the external electric network operates as an electric storage system of infinite capacity [36].

The efficiency gains from CHP vary depending upon technologies and fuel/energy source(s) employed, and the heat and power generation system displaced. Fig. 3 compares the overall efficiencies of CHP and conventional "separate heat and power" generation.

2. Global CHP status

Fig. 4 demonstrates that there are five countries that have successfully expanded the use of CHP to about 30–50% of total power generation: Denmark, Finland, Russia, Latvia and the Netherlands. Each of these countries has its own unique approach, but their collective experience demonstrates what can be achieved.

Table 1 summarizes current estimates for global capacity therefore currently stands at 330 GW_e.

Fig. 5 presents results from the same analysis for the G8 and plus five countries, presented in terms of the CHP shares of total national generation.

CHP currently accounts for around 9% of global power generation (IEA 2007c). Its economic potential, however, is likely to be significantly greater. Fig. 6 shows the expected rise in CHP as a share of national electricity generation. Countries are expected to see a small increase until 2015, with a correspondingly larger growth by 2030 as policies are enacted and begin to be widely implemented. As a whole,

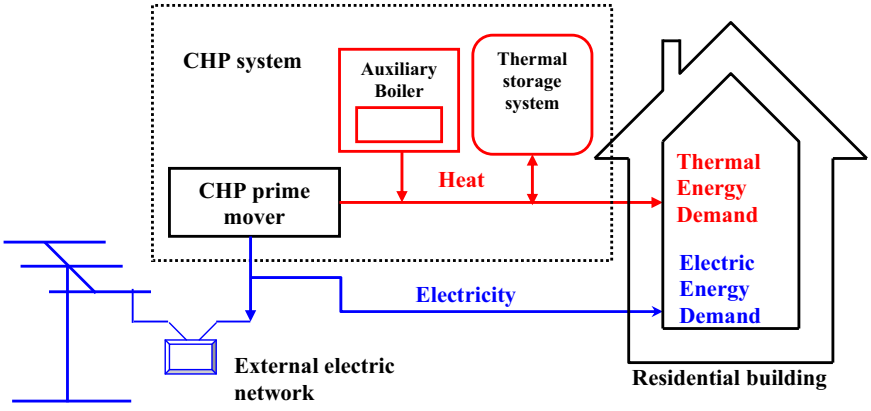


Fig. 2. Lay-out of the CHP system [36].

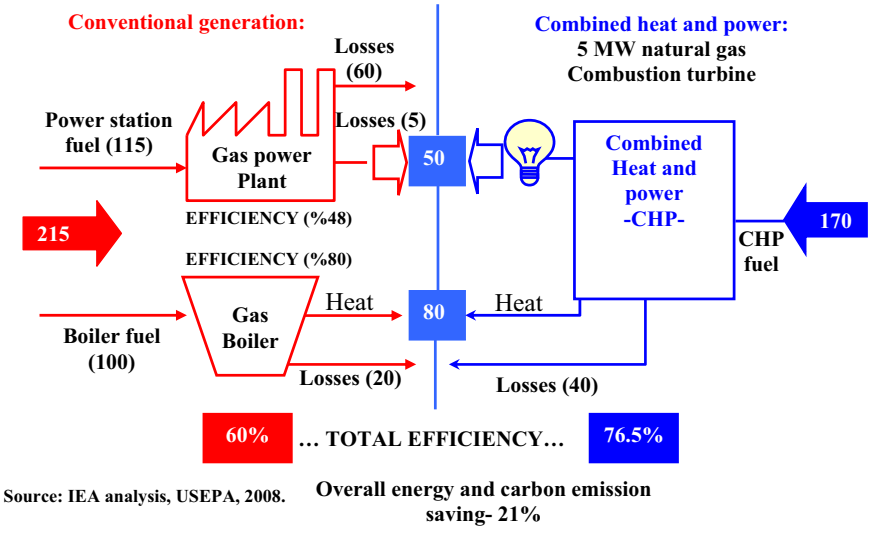
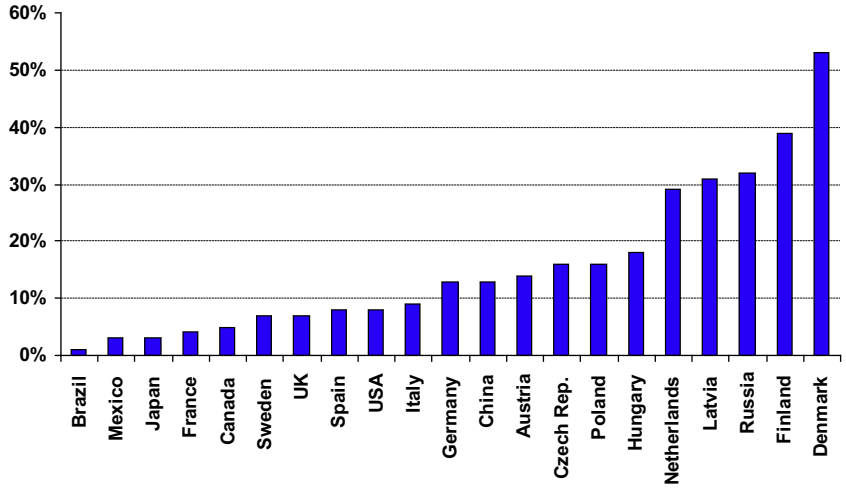


Fig. 3. Efficiency gains of CHP.



Source: IEA data and analysis: data merged from years 2001, 2005, 2006.

Fig. 4. CHP share of total national power production.

Table 1
Installed CHP capacities (MW_e).
Source: IEA data and analysis.

Australia	1,864	Greece	240	Portugal	1,080
Austria	3,250	Hungary	2,050	Romania	5,250
Belgium	1,890	India	10,012	Russia	65,100
Brazil	1,316	Indonesia	1,203	Singapore	1,602
Bulgaria	1,190	Ireland	110	Slovakia	5,410
Canada	6,765	Italy	5,890	Spain	6,045
China	28,153	Japan	8,723	Sweden	3,490
Czech Repub.	5,200	Korea	4,522	Taiwan	7,378
Denmark	5,690	Latvia	590	Turkey	790
Estonia	11,600	Lithuania	1,040	United Kingdom	5,440
Finland	5,830	Mexico	2,838	United States	84,707
France	6,600	Netherlands	7,160		
Germany	20,840	Poland	8,310		

in the G8+5 the share of CHP rises from 11% of electricity generation today to 15% in 2015 and 24% in 2030.

CHP application and fuel use will vary greatly depending on the country concerned. For example in China, a considerable proportion of CHP in the short-term is likely to be based on coal and used in district heating and industrial applications. In the period to 2030, greater use of natural gas and renewable fuels is envisaged, with the development of smaller applications providing both heating and cooling at the individual building level. In France, by contrast, gas is likely to be the predominant fuel for CHP in the short term with the share of renewable fuels growing as the market moves beyond 2015. Fig. 7 presents the potential highlighted in Fig. 6 in CHP capacity terms, based on expected load factors that again take into account different national circumstances. Under the ACS, the G8+5 countries reach almost 430 GW_e of CHP capacities in 2015 and over 830 GW_e in 2030.

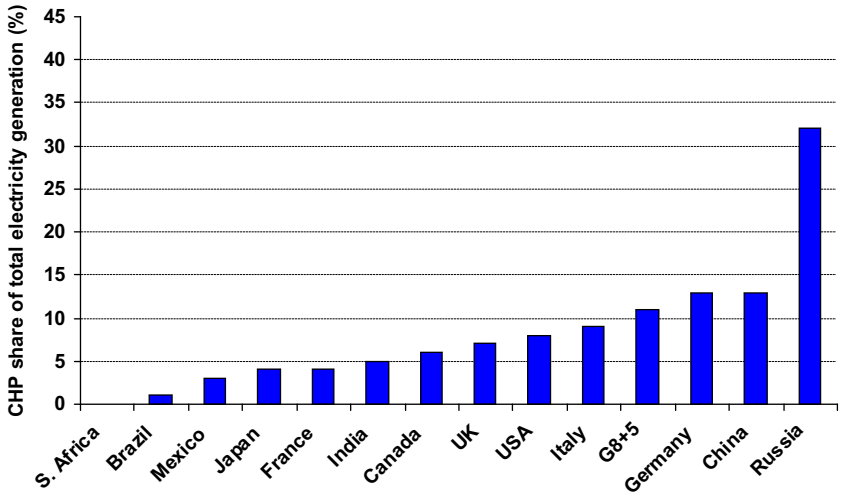
Fig. 8 presents the same data as Fig. 6, but provides a ranking of countries for the two years 2015 and 2030.

3. Current MCHP energy and emissions

A number of studies have investigated the cogeneration systems integrated in individual buildings using whole-building and systems simulation tools and compared their environmental performance with the other supply options. Both building types and grid electricity generation mix are of national, regional or even municipal character, and the results of performance assessment studies may vary accordingly. In the following, some typical studies are referenced, focusing on Central European countries when considering such regional factors. In the Belgian context, Voorspools and D'haeseleer [37] studied MCHP and mini CHP as well as the dynamic interaction between the cogeneration and central power systems [38]. For Germany, Bruckner et al. [39] already showed that cogeneration offers considerable scope for energy savings on a municipal level. Lindenberger et al. [40] showed gas internal combustion engine (ICE) micro-cogeneration units to achieve cost savings and 20% (non-renewable primary) energy savings in comparison with a configuration with gas-fired condensing boiler and national grid electricity with the German electricity production mix. The technological and environmental aspects of building-integrated cogeneration are also covered by Entress [41] comprehensively, especially in terms of life cycle analysis and for fuel cells, by Pehnt [42–44]. The CO_2 reduction potential of MCHP in the Swiss context was evaluated by the authors such as Rognon [45].

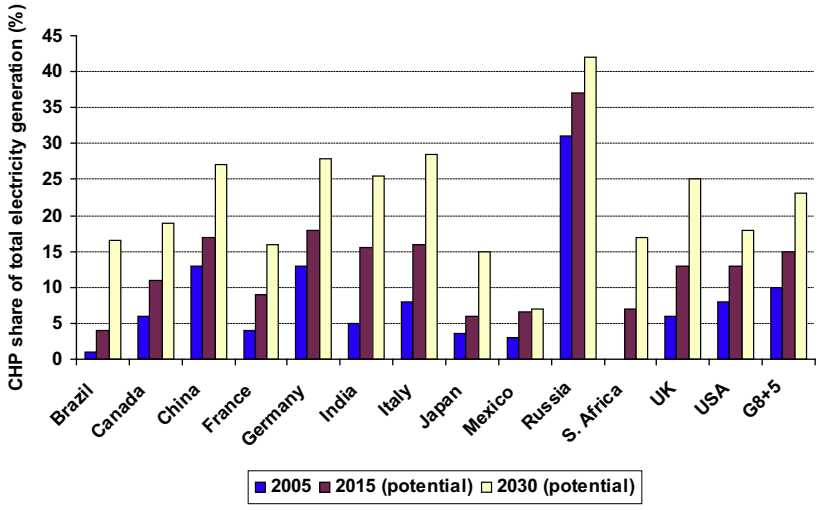
Control strategies and modes were shown to have significant effects on energy and environmental system performance. In many cases, heat-following modes exhibited the best efficiency for energy, and electricity-following control modes for cost, but combined control modes were shown to be most effective in certain cases [46,47]. Micro-CHP for residential buildings in Japan is analyzed in [48]. In this analysis, it was found that the introduction of Micro CHP systems results in large economic merit due to the incentive policies issued by the government and gas companies. In [49], technical and economic feasibility studies of using Micro CHP systems in different climate zones of Iran are performed from both economic and environmental viewpoints. This study drew the same general conclusions as the previous. As a base of the calculation, the evaluation of dwelling energy demands (i.e. thermal, electricity and cooling demand for air conditioning) is required. The thermal demand, considered as the sum of space and hot-water heating, is evaluated by following the legislation for the energy certification of buildings [50]. The annual specific thermal request depends on the climate zone of the dwelling and on the characteristics of the building (i.e. surface/volume ratio, degree of dispersion and transmittances) [36]. The effect of the incentives, both granted to natural gas and electricity in CHP applications is investigated in detail in [51].

The efficiencies of an MCHP system under real operating conditions can be considerably lower than those of the MCHP device alone when operating at full load. Start-up and shut-down cycles and thermal losses from heat storage were associated to such performance reductions for a Stirling engine device in a



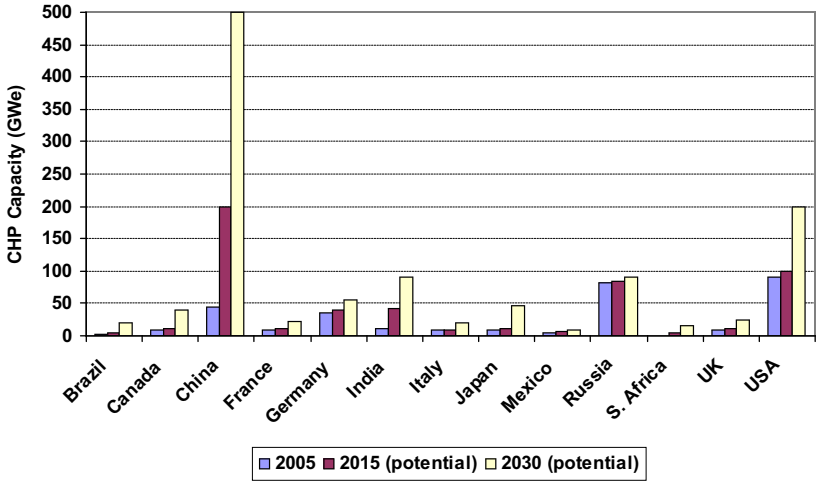
Source: IEA data and analysis: data merged from years 2001, 2005, 2006.

Fig. 5. G8 & 5 countries: CHP as a share of electricity generation.



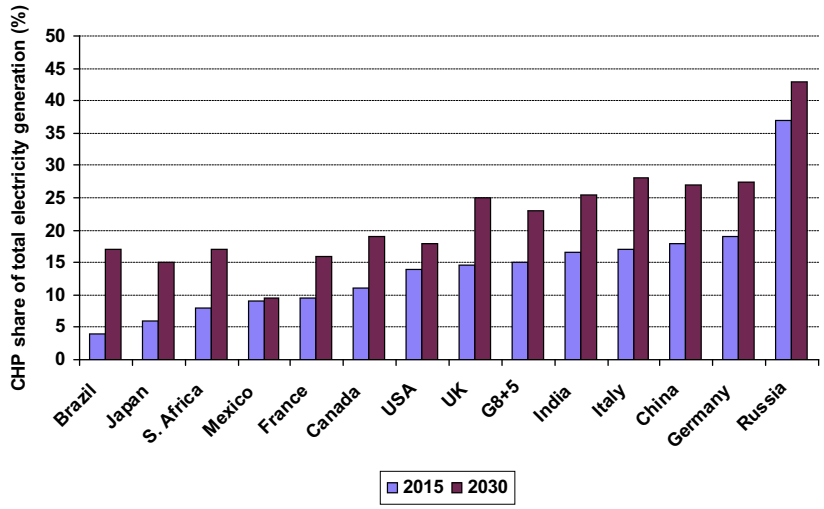
Source: IEA data and analysis

Fig. 6. G8 & 5 countries: CHP potentials under an accelerated CHP scenario, 2015 and 2030.



Source: IEA data and analysis

Fig. 7. Current and projected CHP capacities under an accelerated CHP scenario, 2015 and 2030.



Source: IEA data and analysis

Fig. 8. G8 & 5 countries: CHP share of electricity generation in 2015 and 2030.

Canadian study [52]. MCHP modeling and simulations also form the basis for performance optimizations. To define the sets of optimal configurations, sensitivity analysis [53] or multiple-objective (energy-economic or energy-environmental) optimization techniques were applied, also combining process flow models with process integration methods and multiple-objective optimization [54,55].

The continual uses of fossil fuels to meet our ever-increasing energy demands have led to environmental pollution to air, water and land. The renewable energy sources are alternatives to the depleting fossil fuels and offer improved security of our future energy supply. Biomass energy, a traditional renewable energy source, currently ranks fourth worldwide providing approximately 14% of the world′s primary energy supply. In the developing countries, biomass accounts for approximately 35% or higher of the primary energy supply [56]. Combustion is the most widely used technology to convert bulky, solid biomass feedstocks into useful forms of energy due to its simplicity and maturity. Although biomass combustion releases carbon dioxide (CO_2), similar to the combustion of fossil fuels, it is a CO_2 neutral process as the same amount of CO_2 in the atmosphere is absorbed by the growing biomass plants via photosynthesis a short time (ca. a year to 10 years) ago. In addition, the emissions of SO_x and NO_x from the combustion of many biomass fuels are insignificant, particularly compared to coal combustion. The ever-increasing global energy demand, depleting fossil fuel reserves and global warming require a further increase in biomass energy utilisation for distributed electricity generation and domestic heating in both developing and developed countries. Biomass-fuelled CHP systems can efficiently convert biomass chemical energy into electricity and heat. Biomass energy has its advantage of continuity over the intermittence of solar energy and wind energy. In considering the merits of biomass energy, biomass-fuelled CHP systems have the potential to solve the energy trilemma, i.e., security of supply, affordability of energy and environmental protection [57,58].

Since CHP systems produce two forms of energy in one process, they will provide substantial energy savings relative to conventional separate electric and thermal energy technologies [59]. Mittelman et al. [60] investigated the performance and cost of a CPVT system with single effect absorption cooling in detail and the results showed that under a wide range of economic conditions, the combined solar cooling and power generation plant can be comparable to, and sometimes even significantly better than, the conventional alternative. Medrano et al. [61] developed a simplified model to assess the potential energy, economic and CO_2 savings of the building with non-conventional energy systems such as solar photovoltaic arrays, thermal collectors, an internal combustion engine cogeneration, and an absorption chiller. Also, parametric studies for natural gas and electricity prices as well as results for other possible combinations with only one or several of the installed systems in operation was carried out. Beccali et al. [62] presented a detailed analysis of the energy and economic performance of desiccant cooling systems (DEC) equipped with both single glazed standard air and hybrid photovoltaic/thermal (PV/t) collectors for applications in hot and humid climates and showed the results of detailed simulations conducted for a set of desiccant cooling systems operating without any heat storage. Alanne et al. [63] conducted a comparative assessment of the SOFC system vis-à-vis heating systems based on gas, oil and electricity using the simplified model for a single-family house located in Ottawa and Vancouver and the energy consumption of the house was estimated using the HOT2000 building simulation program and a financial analysis was carried out to evaluate the sensitivity of the maximum allowable capital cost with respect to system sizing, acceptable payback period, energy price and the electricity buyback strategy of an energy utility. For the Netherlands, Laag et al. [64] predicted PE savings of 12% (SE) to 24% (FC) for MCHP applications in an average Dutch household, and Ruijg and Ribberink [65] assessed profitability of PEMFC, SOFC and Stirling (SE) MCHP systems. For SE and fuel cell MCHP systems in UK SFH, Peacock and Newborough [20,21] predicted 9% and 16% of CO_2 emissions savings compared to condensing boiler and grid electricity, and even greater savings for higher power output systems of high efficiency, with larger portions of generated electricity being exported [22]. In several papers, Hawkes et al. examined the techno-economic aspects of MCHP [66,67] and related least-cost optimization strategies [15], and also investigated the influence of temporal precision on the performance results [68]. A comparative CO_2 savings assessment of FC, SE and ICE MCHP and heat pumps for the UK domestic sector was made by Cockroft and Kelly [23]. The CO_2 reduction potential of MCHP in the Swiss context was evaluated by authors such as Rognon [45], although not on the basis of detailed building simulations.

Some other works on economic issue of Micro CHP systems are Wood and Rowley [69] on techno-economic analysis of small-scale, biomass-fuelled combined heat and power for community housing, Egeskog et al. [70] on co-generation of biofuels for transportation and heat for district heating systems in EU, Sashirekha et al. [71] present a flexible algorithm to solve the combined heat and power (CHP) economic dispatch problem ([72], combined heat and power economic dispatch problem solution using particle swarm optimization

with time varying acceleration coefficients; [73], cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass; [74], thermo-economic assessment of a micro CHP system fuelled by geothermal and solar energy).

4. Prime mover technologies (CHP technologies)

The CHP technologies suitable to be applied for the heating of residential buildings (mainly systems up to 5–10 kW_e, or, in any case, with an electric power size lower than 100 kW_e) available on the market (even though not yet widespread and industrialized) are those based on the internal combustion engine (ICE), micro gas turbine (MGT), micro Rankine cycle (MRC) and Stirling engine (SE) [27,30,75–77]. The performance of these CHP technologies is summarized in Figs. 9–11. In particular, Figs. 9 and 10 show the various CHP units, the rated electric and thermal efficiency respectively, as a function of the electric power. All values are at the rated electric power and in full heat recovery conditions. Fig. 11 reports the thermal efficiency vs. electric efficiency for various CHP units; lines corresponding to fixed values of the electric-to-thermal power ratio C are highlighted together with the line corresponding to an overall CHP efficiency $\eta_{CHP}=\eta_e+\eta_t=75\%$. Fig. 13 highlights that the CHP technologies based on the MGT are usually characterized by C values slightly higher than ICE, and significantly higher than SE and MRC. These last two technologies, in particular, are characterized by the lowest electric efficiencies (typically between 5% and 20%).

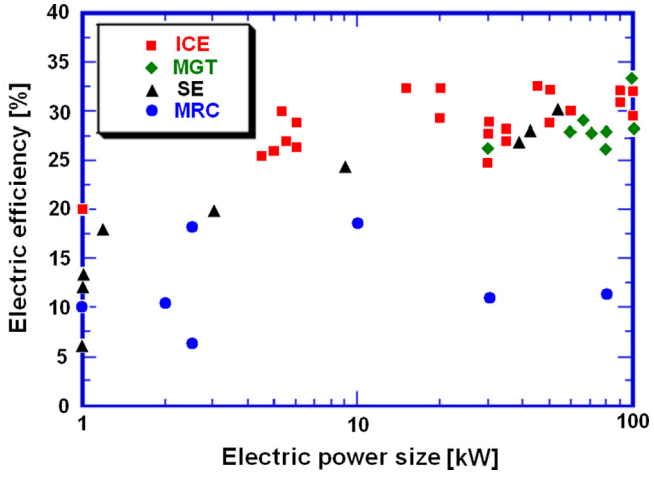


Fig. 9. The rated electric efficiency as a function of rated electric power [36].

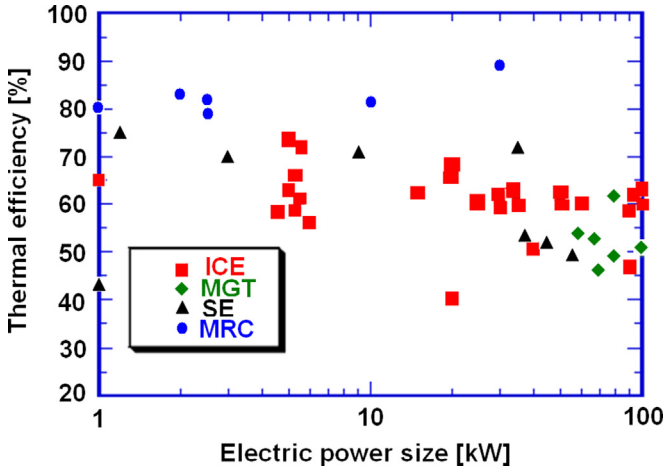


Fig. 10. The rated thermal efficiency as a function of rated electric power [36].

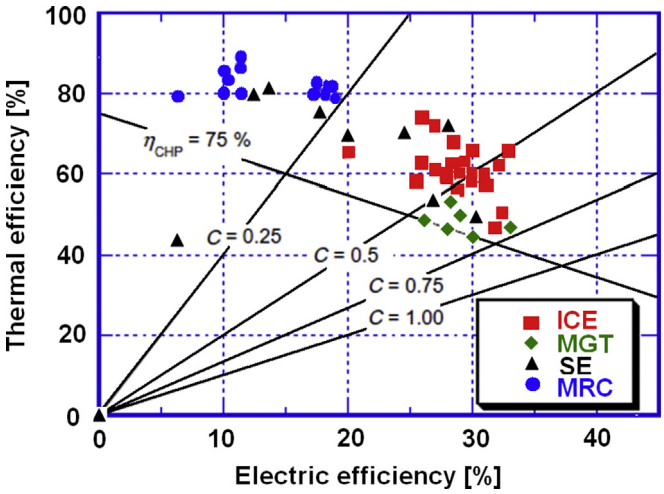


Fig. 11. The points representative of various CHP units (coordinate plane $\eta_e-\eta_t$) [36].

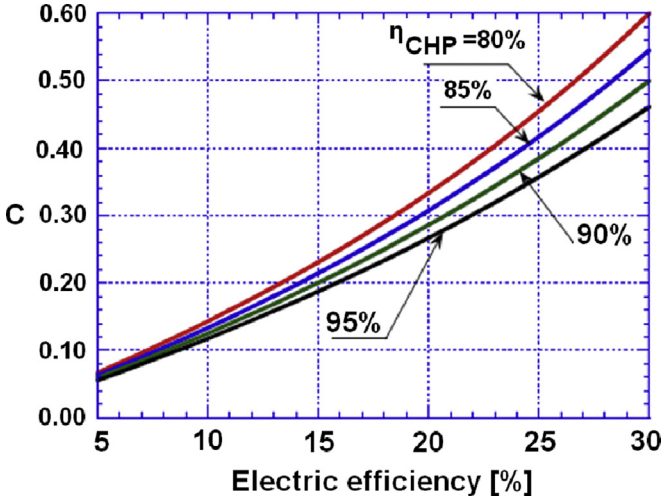


Fig. 12. The link between C, electric efficiency and overall CHP efficiency [36].

It is also interesting to observe that all the available CHP technologies present values of the overall CHP efficiency η_{CHP} higher than 75%. The link among the C values, electric efficiency and overall CHP efficiency is reported in Fig. 12.

The considered Micro CHP systems are based on internal combustion engines (ICE), micro gas turbines (MGT), micro Rankine cycles (MRC), Stirling and thermophotovoltaic (TPV) and fuel cells technologies. The later three technologies are external combustion systems (thus, pollutant emission levels are comparable to those of boilers), characterized by high reliability, low noise, and potentially high values of the overall CHP efficiency. Similarly, Monteiro et al. [78] analyzed three small size CHP systems (based on internal combustion engines, micro gas turbines and Stirling engines).

4.1. Internal combustion engines

Internal combustion engines are the most well-established technology for small- and Micro CHP applications. For applications that suit domestic installations, the electric efficiency ranges from 20% to 26%, with a potential CHP efficiency up to 90% [30,79]. Rosato and Sibilio claimed that internal combustion engine-based

micro cogeneration devices are a market-ready technology gaining an increasing appeal thanks to their high efficiency, fuel flexibility, low emissions, low noise and vibration [80].

4.2. Micro gas turbines

Gas turbines are a well-established technology for Micro CHP applications with electric power outputs higher than approximately 30 kW [30,79,81] (Fig. 13). The major technical factors that challenge the development of micro turbines of a few kW are related to the small-scale effects (e.g. large fluid dynamics, heat and mechanical percentage losses) and costs [82,83]. To overcome these limitations, Moss et al. present in [84] a recuperated gas turbine, with an electrical and thermal power of 5 kW and 8 kW, respectively, where the centrifugal compressor and turbine are replaced with reciprocating engines. From the simulated results, an electrical generation efficiency of 33% appeared possible. At present, a recuperated micro turbine prototype has been documented [83]. Experimental tests demonstrated an electric power output of 2.7 kW at 12.3% electrical efficiency; nevertheless the authors of paper [83] are reasonably confident that a demonstrator rated at 3 kW with a target electric efficiency of 16% will be available soon. Studies to increase the MGT electric efficiency focus on ceramic materials [85] and hybrid power plants consisting of an MGT integrated with a solid oxide fuel cell [86,87].

4.3. Micro Rankine cycles

The Micro CHP systems based on Rankine cycles (which use water or an organic fluid as the working fluid) with a power size of up to 10 kW, which are mostly available on the market at a prototype level only, have an electric power size ranging from 1 kW to 10 kW, with a corresponding thermal power size ranging from 8 kW to 44 kW (Fig. 14). For this reason, they may represent a good alternative to household boilers. The electric efficiency ranges from 6% to 19%, with a potential overall CHP efficiency that is always higher than 90% [30,79,89–91].

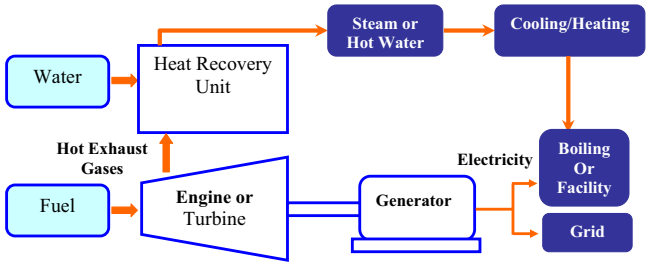


Fig. 13. The schematic representation of micro gas turbine CHP [88].

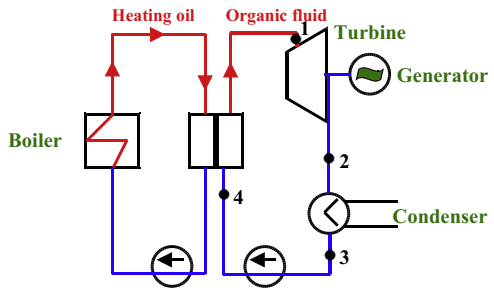


Fig. 14. The schematic of MCHP thermodynamic Rankine cycle [92].

4.4. Stirling engines

The Micro CHP Stirling systems available on the market with an electric power size of up to 10 kW, which are mostly prototypes, have an electric power size ranging from 1 kW to 9 kW and a corresponding thermal power size from 5 kW to 25 kW, which may also represent a good alternative to household boilers. The electric efficiency ranges from 13% to 28% with the CHP efficiency higher than 80%, which may even go beyond 95% [30,77,79].

4.5. Thermo photovoltaic (TPV) generators

TPV-based Micro CHP systems can be obtained from properly designed boilers, which use a surface radiant burner, by placing PV cells in front of the surface radiant burner inside the combustion chamber [30,79,93,94]. All heat not converted into electric energy by the PV cells (such as heat removed from cells by the PV cell cooling system) is usefully recovered. Thus, the extra-fuel supplied for electric energy production with respect to the simple boiler can be considered fully converted into electric energy. Although the electric efficiency of TPV CHP systems is low (approximately 2–5% for available prototypes and in any case less than 15%), the potential CHP efficiency is always higher than 90% [30,79].

4.6. Fuel cells

Fuel cells are electrochemical energy converters similar to primary batteries. Fuel cell Micro CHP systems are either based on the low temperature polymer electrolyte membrane fuel cells (PEFC or PEMFC) which operate at about 80 °C, or on high temperature solid oxide fuel cells (SOFC) working at around 800–1000 °C [95]. Fuel cells can form the basis of a micro cogeneration system. In order to be viable, fuel-cell based micro cogeneration systems must be competitive with current combined-cycle fossil fuel power plants that have net electrical efficiencies of approximately 55% relative to the fuel's lower heating value (LHV). As fuel-cell micro cogeneration is unlikely to achieve this electrical efficiency level, the effective use of the heat production is necessary to compete with efficient central power plants [10]. Fuel cells can reach large production numbers by attaining different mass markets, e.g. in the automotive sector, as a de-central storage technology for fluctuating generation from renewable energy sources or as a de-central cogeneration technology [96]. In all of these potential markets, they face a number of competing technologies. Price projections based on learning curves for PEM fuel cells reveal that the necessary economies of scale can hardly be achieved without subsidies before 2025 [97]. Until today, related scientific literature covers mainly operational strategies of MCHP fuel cells [98] or integration into existing liberalised power markets. One of the results is that the ability for variable operation is desirable if MCHP units should be able to participate in different kinds of electricity markets and adjust to market signals [99–101]. General system interactions of an SOFC based MCHP is shown at Fig. 15.

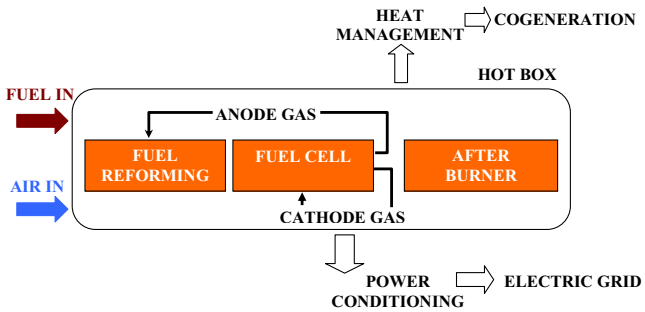


Fig. 15. The general system interactions of an SOFC based MCHP [102].

In the analysis of a 1 kW CHP system based on solid oxide fuel cell, Xu et al. found that the SOFC-CHP system designed can produce 1.005 kW electric power and 0.521 kW heating power. The system electric efficiency of 52.1% and cogeneration efficiency of 79.2% can be achieved respectively. The cell output voltage, system inlet fuel flow rate, and SOFC stack inlet air temperature affect the system greatly and non-monotonously. The resulting performance characteristics are obtained, which are of great significance for the design, optimization and safe operation of SOFC-CHP systems [103].

Wongchanapai et al. combined a direct-biogas solid oxide fuel cell (SOFC) with a micro gas turbine (MGT) system which offers great potential as CHP system (Fig. 16). To evaluate this system a sensitivity analysis was conducted under diverse operating conditions to investigate the influence of key operating parameters of the hybrid CHP system with the consideration of operational constraints. The increase in fuel utilization factor (U_f) improves the electrical power output produced by the SOFC stack, but also requires more fuel to be fed to the burner, resulting in an increase in useful heat energy. Increasing the compression ratio improves the system electrical efficiency but lowers useful heat generation; nevertheless, increasing turbine inlet temperature (TIT) decreases the system electrical efficiency but improves the efficiency of the CHP system. To achieve the optimum operating conditions of the hybrid CHP system, the operating parameters should be determined based on the desired energy outcomes [104].

Xie et al. by energy and exergy analysis of a fuel cell based micro combined heat and power cogeneration system found that for the typical case, energy carried by unuseful streams accounts for the majority of the energy and exergy losses. Among all the components, proton exchange membrane fuel cell posses the least energy efficiency and exergy efficiency [105].

4.7. Prime movers for single family users

The prime movers available on the market (mostly at a prototype level only) with electric power up to 5 kW and suitable for residential single family users are reported in Table 2 [30,79,83,106–118]. It can be noted that the prime movers are characterized by considerably different values of electric and thermal efficiency. As regards the overall CHP efficiency η_{CHP}, it has to be noted that all the prime movers allow η_{CHP} values equal or higher than 84%. The prime movers considered for the analysis carried out in this paper, one technology, are highlighted in gray in Table 2. These systems were selected as the most suitable prime movers for single family residential users. In particular, the electric efficiency of the considered MGT (16.0%) and TPV generator (12.3%) has to be considered as a target value [36].

Arsalis et al. [8] investigated a 1 kW_e HT-PEMFC (high temperature-proton exchange membrane fuel cell)-based residential Micro CHP (combined-heat-and-power) system for Danish

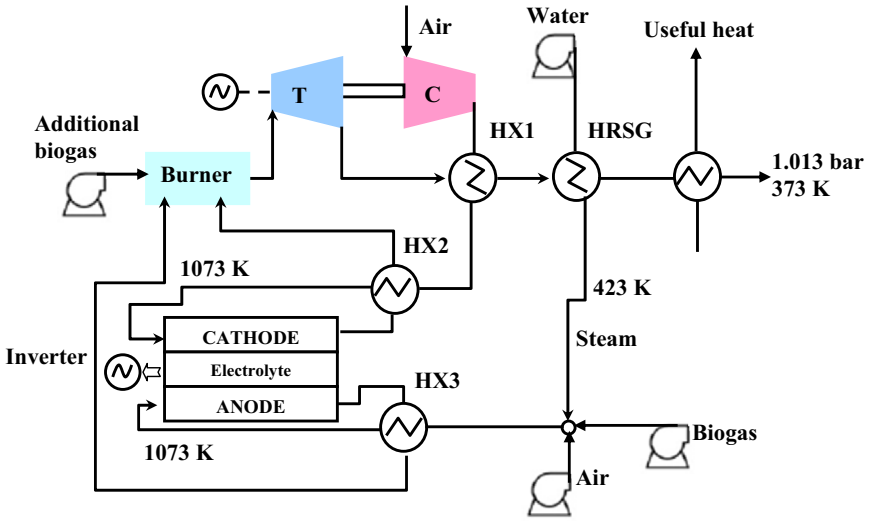


Fig. 16. The schematic flow diagram of the direct-biogas SOFC-MGT hybrid CHP system [104].

Table 2
Main characteristics of prime movers suitable for single-family dwellings.

Product	Technology	Electric output (kW)	Electric eff. (%)	Total eff. (%)	Reference
Baxi Ecogen	Stirling	1	15	91	[95]
DISENCO	Stirling	3	18.4	92	[117]
INFINIA	Stirling	1	12.5	92.5	[114]
Vaillant ecoPower 1.0/Honda ECOWILL	Gas engine (ICE)	1	26	92	[106,95]
AISIN SEIKI	Gas engine (ICE)	4.6	25.5	84	[107]
Senertec (DACHS)	Gas engine (ICE)	5	26	89	[108]
Panasonic Ene-farm	Fuel cell, PEM	1	35	85	[95]
Hexis Galileo 1000N	Fuel cell, SOFC	1	30	90–105	[95]
CFCL BlueGen	Fuel cell, SOFC	1.5	60	<85	[95]
Energetix	Micro Rankine cycles (MRC)	1	10	90	[110]
OTAG	Micro Rankine cycles (MRC)	2	10.4	94	[111]
COGEN Microsystems	Micro Rankine cycles (MRC)	2.5	18.5	99.9	[112]
MTT	Micro gas turbines (MGT)	3	16	96	[109,83]
JX Crystal	Thermophotovoltaic (TPV)	1.5	12.3	92.1	[118]

single-family households. As they said An HT-PEMFC operates at elevated temperatures, as compared to Nafion-based PEMFCs and therefore can be a significant candidate for cogeneration residential systems. The proposed system can provide electric power, hot water, and space heating for a typical Danish single-family household [119]. From an energy point of view, the considered CHP systems usually satisfy most of the thermal and electric energy demand, with a primary energy saving index that is always higher than 20%. As regards economic feasibility, it is shown that a reasonable target for the marginal cost of a CHP system for household heating is approximately 3000 €/kW_e. It is also shown that the highest profitability can be obtained by using the prime mover (i) with the lowest electric power output closest to that of the peak electric demand and (ii) with an electric-to-thermal ratio which fits the electric-to-thermal ratio of the users [51].

Table 3
The benefits and costs of CHP compare to other clean energy technologies.
Source: EPA: United States Environmental Protection Agency http://www.epa.gov/.

Category	10 MW CHP	10 MW Wind	10 MW Natural gas combined cycle
Annual capacity factor	85%	34%	70%
Annual electricity	74,446 MW h	29,784 MWh	None
Annual useful heat	103,417 MW h_t	None	103,417 MW h_t
Footprint required	6,000 sq ft	76,000 sq ft	N/A
Capital cost	$ 20 million	$ 24.4 million	$ 9.8 million
Cost of power*	7.6 ĉ/kW h	7.5 ĉ/kW h	6.1 ĉ/kW h
Annual energy saving	316,218 MMBtu	306,871 MMBtu	163,724 MMBtu
Annual CO_2 saving	42,506 t	27,546 t	28,233 t
Annual NO_x saving	87.8 t	36.4 t	61.9 t

5. CHP is more efficient than conventional electricity generation

CHP is a form of distributed generation, which is located at or near the energy-consuming facility, whereas conventional generation takes place in large centrally-located power plants. CHP′s higher efficiency comes from recovering the heat normally lost in power generation or industrial processes to provide heating or cooling on site, or to generate additional electricity. CHP′s inherent higher efficiency and elimination of transmission losses from the central power plant results in reduced primary energy use and lower greenhouse gas (GHG) emissions.

CHP reduces energy cost for the user, CHP reduces the risk of electric grid disruptions and enhances energy reliability for the user, this is particularly useful for hospitals, research institutions, or industrial facilities where electric power outages are particularly disruptive and costly and CHP provides predictability in the face of uncertain electricity prices Table 3.

Fig. 17 shows how CHP systems can be cost effective compared with other forms of power generation and average retail electricity rates. As CHP systems generate useful electricity and thermal energy, one justifiable and reasonable way to account for these dual benefits is to apply the value of the useful thermal energy to lower the effective cost of electricity generated. Fig. 17 illustrates this by the application of a “thermal credit” to the cost of delivered electricity.

Capital cost assumptions for different technologies has been specified at Table 4.

6. Using renewable energy in Micro CHP systems

Hessami [120] described three electricity and/or heat generation applications fuelled by biogas or landfill gas produced from

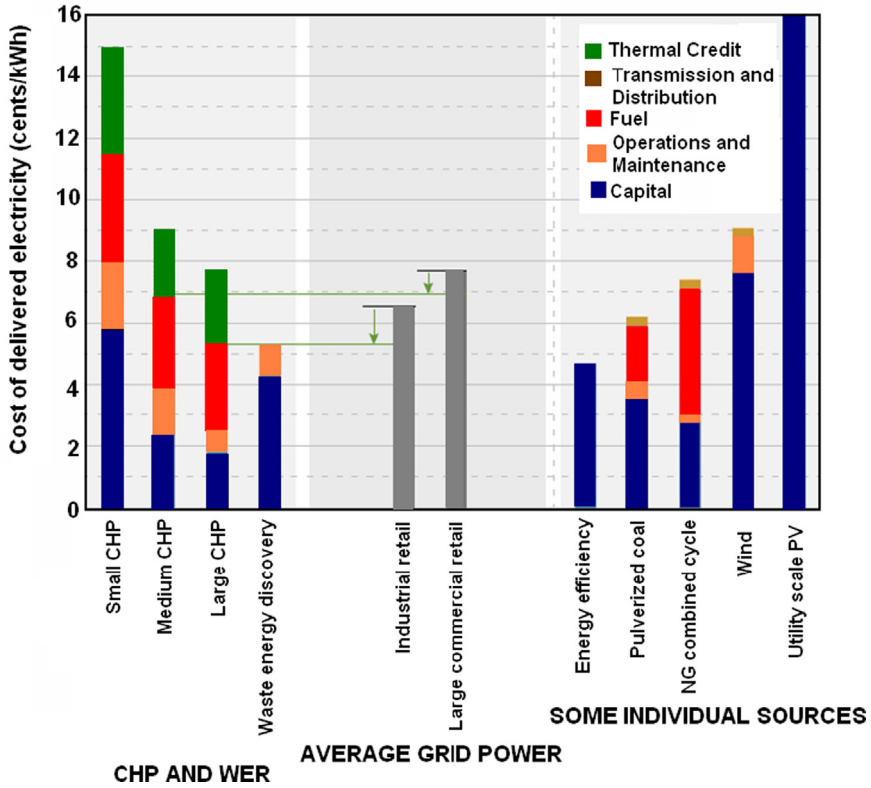


Fig. 17. Systems are cost-competitive in industrial and commercial sectors [152].

Table 4
Capital cost assumptions..Source: IEA data and analysis

Technology	2005 cost (USD/kW)	Change 2005–2015 (%)	Cost 2015–2030 (USD/kW)
Coal	1350	0	1350
Oil	1340	0	1340
Gas	570	0.5	627
Nuclear	2250	1.0	2718
Wind	1500	−1.0	1239
Solar	3600	−5.0	1358
Hydro-electric	2500	0	2500
Biomass	1600	−2.0	1090
Gas CHP	1324	0	1324
Coal CHP	2766	0	2766
Biomass CHP	2568	−2.0	1750
Gas micro-CHP	2500	0	2500

organic waste material and noted that CHP is currently the most suitable energy management strategy to produce both heat and power. Murphy and Mckeogh [121] investigated four technologies, which produce energy from municipal solid waste (MSW): incineration, gasification, generation of biogas and utilization in a combined heat and power (CHP) plant, generation of biogas and conversion to transport fuel. Dong et al. [14] carried out a review on the development of small land micro-scale biomass-fuelled combined heat and power systems concentrating on the current application of organic Rankine cycle (ORC) in small- and micro-scale biomass-fuelled CHP systems and compared ORC with other technologies such as biomass gasification and micro-turbine based biomass-fuelled CHP systems. Gustavsson [122] observed that new technologies for biomass gasification are being developed which increase the potential to cogenerate electricity and may reduce costs compared with steam turbine technology and discussed its potential to cogenerate electricity in the Swedish district-heating systems. Larson [123] reviewed biomass integrated-gasifier/gas turbine combined cycle (BIG/GTCC) designs and ongoing demonstration and commercial projects and presented estimates of the performance of two different BIG/GTCC plant configurations integrated into sugar or sugar-and-ethanol factories and concluded with an assessment of the potential impacts on the Cuban energy sector of the introduction of BIG/GTCC cogeneration systems in that country′s sugarcane industry. Uddin and Barreto [124] analyzed biomass-fired cogeneration plants based on steam turbine technology (CHP-BST) and integrated gasification combined cycle technology (CHP-BIGCC) and estimated the CO_2 mitigation costs of large-scale biomass-fired cogeneration technologies with CO_2 capture and storage. Prasad [125] explored potential for using biomass sources in Fiji for the generation of industrial process steam and rural electricity. Bianchi et al. [126] studied the utilization of the organic wastes from an existing poultry industry as fuel, considering different plant configurations, in order to make use of the oil and of the meat and bone meal, which are the by-products of the chicken cooking process. Tillman and Jamison [127] carried out a review on four basic cogeneration cycles: the steam turbine topping cycle, the gas turbine topping cycle, the diesel topping cycle, and the bottoming cycle and found that the steam turbine topping cycle is most appropriate for wood. Sipila [128] has given an overview on how combined heat and power production is widely used and is an efficient way to reduce CO_2 emissions in Scandinavia, as well as to some extent elsewhere in Europe and discussed several basic and applied research as well as pilot activities has been carried out in research organizations and in industry in Finland in the area of solid-biomass IGCC technology. Shuying et al. [129] described a project that is being co-funded by the Jilin Provincial Government and the United Nations Development Program to demonstrate the technical, economic and market viability of amodern biomass gasification system to provide cooking gas, heat and electricity to village communities in China. Pellegrini et al. [130] presented a comparative thermo-economic study of biomass integrated gasification combined cycle systems for sugarcane mills. Gustavsson and Johansson [131] addressed the potential for bioenergy in Sweden and compared different means of using bioenergy in the electricity, heat, and transportation sectors.

Some other works which are on using renewable energies in Micro CHP systems are Rheinländer and Lippke [132] studied the cogeneration of electricity and potable water utilizing solar energy, assuming solar tower power plants with the open volumetric PHOEBUS receiver and the results for alternative plant configurations show that the water production cost is about the same or even lower than the cost of water produced by conventionally fired systems. Pearce [133] investigated the potential of deploying a distributed network of PV–CHP hybrid systems in order to increase the PV penetration level in the U.S and the temporal distribution of solar flux, electrical and heating requirements for representative U.S. single family residences were analyzed and the results clearly showed that hybridizing CHP with PV can enable additional PV deployment above what is possible with a conventional centralized electric generation system. Prengle et al. [134] discussed, in detail, a 100 MW_e central receiver—AHS cycle cogeneration power plant and cycle analysis, preliminary cost estimates, and unit energy costs are also discussed. Moustafa et al. [135] described a 100 kW_e/700 kW^{th} distributed receiver; solar-thermal power plant, that was installed in remote desert location 35 km southwest of Kuwait City in the country of Kuwait, designed to supply the electric power and fresh water, needs of a small agricultural desert settlement. Dufour [136] studied the impact fuel cells could have on electrical grid management and control, for their voltage support and active filtering capabilities, for their response speed and for quick load connection capabilities. Alcaide et al. [137] presented a review of specific fuel cells (FCs) with ability to produce useful chemicals and also generate electricity at the same time and classified the chemical cogeneration processes according to the different types of fuel cells and it was shown that a flow alkaline FC (AFC) is able to produce hydrogen peroxide. Figueroa and Otahal [138] focused on the strategy and experience of San Diego Gas and Electric with the development and demonstration of a proof of concept 250-kW internally manifolded heat exchanger (IMHEX®) carbonate fuel cell power plant and discussed the following topics: (i) SDG&E′s involvement in the development of molten carbonate fuel cell (MCFC) technology; (ii) the active role in engineering and specification of the IMHEX® MCFC demonstration plant; (iii) responsibility for installation, commissioning, and operation; (iv) utility role in technology development and application of MCFC in a restructured and competitive environment. Al-Rabghi et al. [139] presented a review of waste heat recovery and utilization and discussed the potential for re-using the otherwise wasted heat in different branches of industry and traditional and new ways to recover the discharged heat from industrial equipment were illustrated and it was concluded that there exist numerous opportunities for recuperating and using waste heat. In Ref. [14], a review is carried out on the development of small- and micro-scale biomass-fuelled combined heat and power (CHP) systems. Discussions have been concentrated on the current application of organic Rankine cycle (ORC) in small- and micro-scale biomass-fuelled CHP systems ([140], biomass integrated gasification combined cycle for heat and power at ethanol plants; [141], dynamic simulation of a solar-driven carbon dioxide transcritical power system for small scale combined heat and power production; [142], effective biomass integration into existing combustion plant; [143], energetic and environmental performance of three biomass upgrading processes integrated with a CHP plant;

[144], limiting biomass consumption for heating in 100% renewable energy systems; [145], model of a small steam engine for renewable domestic CHP system; [146], modeling fuel terminals for supplying a CHP plant with forest biomass in Finland; [147], techno-economic evaluations of various biomass CHP technologies and policy measures under Norwegian conditions; [148], the economic performance of combined heat and power from biogas produced from manure in Sweden).

7. Applications of Micro CHP plants

The main potential of Micro CHP systems is mainly seen in buildings with central heating systems. This generally means that conventional heating systems are replaced by electricity generators with heat exchanger(s), peak load and storage boilers. The produced heat is used for space and water heating and possibly cooling, the electricity is used within the building or fed into the grid (Fig. 18).

In a study on energy, economic and environmental analysis of a Micro Gas Turbine for on-site CHP production, Ehyaei and Mozafari found that that the initial investment is a considerable portion of electricity cost. For an annual interest rate of 10% this portion ranges from 31% to 40% depending on system design configurations, and the lower interest rates results in the smaller portions. It is also concluded that the number of turbine units and electricity cost are highly dependent on electricity consumption management [149].

In the last few years a trend for the usage of Micro CHP units in isolated regions could be monitored. Especially buildings with no grid connection and/or less reliable electrical energy supply were using Micro CHP systems in connection with battery systems and hot water tanks. Moreover instead of using diesel as fuel, nowadays environmentally friendly rape oil and/or biodiesel is used in these Micro CHP systems. Especially in ecological sensible regions like mountains due to reasons of air-, soil- and water/groundwater conservation, etc. these systems have decisive environmental advantages (especially in case of usage of natural untreated rape oil).

In the past, several studies have been carried-out in order to determine the potential of Micro CHP units in Europe. For example, studies, such as Micro Map [88] see a large potential for Micro CHP plants. They developed scenarios according to which in 2020 some 5 to 12 million Micro CHP systems could be delivered in Europe, with United Kingdom, Germany and Netherlands as initial markets. Micro Map concluded that Stirling engines have the highest potential in domestic energy supply. The future Cogen project estimated that under optimistic assumptions, up to 50 GW_{el} in EU15 could be installed [150]. The mass market for Micro CHP will be mainly seen in the replacement of gas and oil heating boilers.

In spite of the sustainability potential identified above, the European development of Micro CHP systems in competitive markets is rather disenchanting. The large gap between expectations and reality make it important to identify the barriers which are responsible for this discrepancy. Main reasons are seen in the rather slow technology development, in the assessment of the economic opportunities, in the political framework, for example the institutional and regulatory framework, in lacking innovation policies, and consumer acceptance. The necessary steps for planning CHP plants are as follows:

- Determination of the energy demand
- Analysis of the energy costs
- Drawing-up of a concept for the selection of the Micro CHP system
- Concept variations and selection of CHP systems
- The final concept and follow-up activities

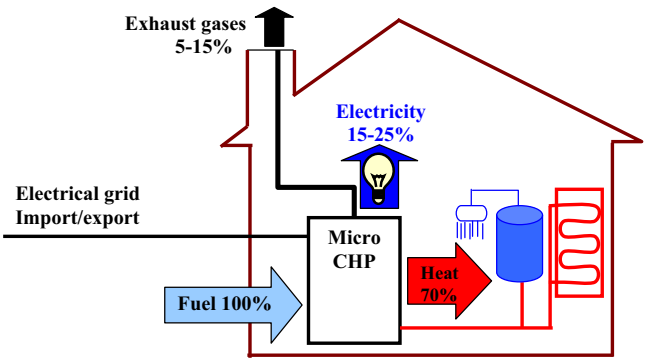


Fig. 18. A general schematic of domestic MCHP [96].

Denntice et al. [11] carried out an investigation on the possibilities of residential Micro CHP systems. They investigated the application of micro cogeneration ($< 15\ kW_e$) to residential and light commercial applications users, conducting an energy analysis of the domestic appliances and evaluating the match between a Micro CHP system and the electrical and thermal requirements of domestic appliances by use of a test facility for Micro CHP modules. They concluded that while the energy saving and the environmental benefits of a micro-scale and on-site cogeneration were undisputed, the technological obstacles still remained against its large diffusion, because a desirable micro cogeneration system with low price and easy-to-use operation for residential end-users was still being under development at the time. Therefore, future introduction of Micro CHP for domestic applications would subject to available technology, matching of electrical and thermal loads, and the gas and electricity prices. Hawkes and Leach [15] studied the third dispatch mode of a Micro CHP system, i.e., the least-cost mode with which the optimized operation conditions are met, besides the heat-led, which is usually the dominant mode, and the electricity-led. Paepe et al. [151] recently evaluated five Micro CHP systems (< 5 kW) for use in residential applications. They found that that all CHP installations can save the primary energy and reduce CO_2 emissions when operated on heat demand. However, installing a Micro-scale CHP in a residential house is not financially favorable at the present time because of high investment cost and long payback period. Therefore, the development of low-cost Micro-scale CHP systems with innovative technologies is urgently needed.

8. Conclusion

Micro CHP products are typically run as heating appliances, providing space heating and warm water in residential or commercial buildings like conventional boilers. But unlike a boiler, Micro CHP systems generate electricity and heat at very high-efficiencies and therefore help to save fuel, cut greenhouse gas emissions and reduce electricity costs. Most units operate in grid-parallel mode, so that the building continues to receive some of its electrical needs from the electrical network, but it may also export some electricity to the network.

This paper discussed the feasibility of Micro-CHP systems, based on internal combustion engines, micro gas turbines, micro Rankine cycles, Stirling engines and thermo photovoltaic generators, to meet household energy demands. Two single-family dwellings were considered and fully characterized regarding their energy performance and daily profiles of electric, thermal and cooling loads. In addition to the PM, the CHP systems are composed of a thermal energy storage unit and an auxiliary boiler used to cover peak thermal demands.

The analysis of energy performance showed that the CHP units usually satisfy at least 80% of the thermal energy demand, while the ratio between the produced and the required electric energy usually remains lower than approximately 85%. The primary energy saving index (in the range of about 20–28%) only depends on the prime mover technology, while the correct sizing of the thermal energy storage unit capacity proved crucial to maximize the absolute value of the saved primary energy. A detailed literature survey of cogeneration technologies based on renewable energy sources like biomass, solar energy, fuel cell, and waste heat was performed.

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